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TITLE: HYBRID POWER SUPPLY

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HYBRID POWER SUPPLY

BACKGROUND

This invention relates to powering of portable electronic devices.

Portable electronic devices are normally powered with either a primary or a rechargeable battery. Growth in the portable electronic device market, as well as, changes in usage patterns, has provided opportunities for the integration of both primary and rechargeable sources of power to power an electronic device. While primary batteries have a greater energy density, their internal resistance is larger, and primary batteries are less suitable in high drain (>0.2C rate of discharge) electronic devices. Rechargeable batteries can handle large loads but do not have sufficient energy capacity for many applications.

SUMMARY

According to an aspect of the invention, a hybrid power supply includes a switching type DC/DC boost type converter that receives energy from a primary battery cell and is arranged to deliver the energy to a rechargeable cell, set to provide a fixed output voltage that is less than the full charge voltage of the rechargeable cell.

According to an additional aspect of the invention, a hybrid power supply includes a switching type DC/DC boost type converter that receives energy from a primary cell and is arranged to deliver the energy to a rechargeable cell and a circuit disposed to control the switching type DC/DC converter. The circuit includes a resistor voltage divider coupled to the feedback input of the converter, selected to provide a fixed output voltage that is less than the full charge voltage of the rechargeable cell.

According to an additional aspect of the invention, a method of operating a hybrid power supply includes delivering energy from a primary cell to a rechargeable cell through a switching type DC/DC boost type converter at a fixed voltage that is less than the full charge voltage of the rechargeable cell.

One or more aspects of the invention may include one or more of the following advantages.

The circuit can take advantage of charging voltage characteristics of Li- ion or Li-polymer rechargeable batteries. For example, the charge voltage of Li- ion batteries is conveniently related to their state of charge over a wide range. This allows the circuit to produce an output voltage from the DC/DC converter 12 at a level that corresponds to a desired state of charge. The circuit does not fully charge the rechargeable battery, sacrificing a percentage of the maximum continuous runtime of the device. But, the non-fully charged arrangement provides the following advantages. The circuit provides a higher energy efficiency of the rechargeable battery. At the end of charge of a rechargeable battery heat losses are produced. By avoiding maximum charge such losses are avoided. Also the rechargeable battery has a lower self-discharge rate (because of a lower charging voltage). In addition, there is minimization in damage from long-term storage. If the rechargeable battery is stored at full charge, the Li- ion battery will permanently lose part of its capacity. Also the circuit minimizes the need for a charge controller and protection circuit.

The circuit also loosens accuracy requirements for the DC/DC converter circuit. Li- ion chargers have typically better than 0.5% accuracy in the output voltage. This typically requires a second charging device after the DC/DC converter. Without fully charging the Li- ion cell allows for a +/- voltage tolerance allowing use of simple and inexpensive DC/DC converters. The circuit allows for a narrow voltage range at the device power supply terminal (which makes the device internal voltage regulation more efficient). The circuit automatically compensates for the amount of energy used from the rechargeable battery and provides a circuit having a very low quiescent current characteristic. The circuit efficiently uses the primary battery energy, has low EMI levels and can be integrated into existing Li- ion powered devices

The details of one or more embodiments of the invention are set forth in the accompanying drawings and the description below. Other features, objects, and advantages of the invention will be apparent from the description and drawings, and from the claims.

DESCRIPTION OF DRAWINGS

FIG. 1 is a block diagram of a hybrid DC power supply.

FIG. 2 is a schematic diagram of a control circuit for the hybrid DC power supply.

FIG. 3 a schematic diagram of an alternate control circuit for the hybrid DC power supply.

DETAILED DESCRIPTION

Referring to FIG. 1, a hybrid power supply 10 includes a switching type DC/DC boost type converter 12 that receives energy from a primary cell 14 and delivers the energy to a secondary, e.g., rechargeable cell 16. The rechargeable cell 16 delivers power, as needed, to the device 20. The device 20 can be any type of electronic device, especially a portable device such as a wireless device, e.g., a cell phone, personal digital assistant, digital camera, and so forth. The switching type DC/DC boost type converter 12 is configured to provide a fixed output voltage that is less than the charging voltage of the rechargeable cell 16, and is current limited to a portion of the charging current of the rechargeable cell. In this configuration, the switching type DC/DC boost type converter 12 acts also as a charger for the secondary battery. The rechargeable cell 16 can be a rechargeable Li-Ion type. Preferred examples include a Li-Ion or Li-Polymer rechargeable cell. These rechargeable cells can provide power to a device 18 for relatively long periods of time compared to other potential rechargeable cells, and can be effective over long periods of continuous use. Primary power sources 14 may include, but are not limited to alkaline, zinc-air, and fuel cells.

By using Li- ion or Li- polymer rechargeable batteries the circuit 10 can take advantage of charging voltage characteristics of such batteries. For example, the charge voltage of Li- ion batteries is conveniently related to their state of charge over a wide range. This allows the circuit 10 to produce an output voltage from the DC/DC converter 12 at a level that corresponds to a desired state of charge. For example, at a voltage of about 4V, the level is about 90 % of the charge voltage. The circuit 10 does not fully charge the rechargeable battery 16, sacrificing 10% of the maximum continuous runtime of the device 20. But the non-fully charged arrangement provides the following advantages. The circuit 10 provides a higher energy efficiency of the rechargeable battery 16. At the end of charge of a rechargeable battery 16 heat losses are produced. By avoiding maximum charge such losses are avoided. Also the rechargeable battery 16 has a lower self-discharge rate (because of a lower charging voltage). In addition, there is minimization in damage from long-term storage. If the rechargeable battery 16 is stored at full charge, the Li- ion battery will permanently lose part of its capacity. Also the circuit 10 minimizes the need for a charge controller and protection circuit.

The circuit 10 also loosens accuracy requirements for the DC/DC converter circuit 12. Li- ion chargers have typically better than 0.5% accuracy in the output voltage. This typically

requires a second charging device after the DC/DC converter. Without fully charging the Li- ion cell allows for a +/- 2.5% voltage tolerance, from 3.9 to 4.1V, which is the output voltage accuracy typical of simple and inexpensive DC/DC converters. The circuit 12 eliminates potential to overcharge the Li- ion battery, resulting in a simplified protection circuit (not shown). The circuit 10 allows for a narrow voltage range at the device power supply terminal (which makes the device internal voltage regulation more efficient). The circuit 10 automatically compensates for the amount of energy used from the rechargeable battery 16 and provides a circuit having a very low quiescent current characteristic. The circuit 10 efficiently uses the primary battery energy, has low EMI levels and can be integrated into existing Li- ion powered devices.

A charge requirement for Li- ion cells is to limit the charge current. The converter itself could limit the charge current. In this way, the step- up voltage converter acts also as a charger to the Li+ battery, acting as a constant current source until the rechargeable battery voltage levels to the converter output voltage, and as a constant voltage source after this point. After the output voltage is reached, the current will drop exponentially to virtually zero in few hours. The system in this state drains negligibly low quiescent current (tens of uA).

Typical converters control the secondary (charging) current and keep the charging current at a constant level; other converters provide no current control. Constant current on the secondary side results in variable current on the primary battery and increases as the voltage on the primary battery decreases. This is a constant power type of discharge and is least favorable for a primary battery. To avoid this the circuit includes the primary battery current control, which senses the primary battery current, and takes part in the closed feedback loop of the DC/DC converter, to assure a low constant current discharge on the primary side, greatly improving the primary battery efficiency.

One drawback is the initial delay, needed for the Li- ion cell to get enough charge to operate the device, especially after replacing the primary battery. A good solution is to monitor the primary battery voltage in the device (through a fuel gauge, low- battery warning and cutoff) and prevent further discharge of the secondary cell. In this way, when the primary battery is discharged, and the rechargeable battery is still nearly fully charged, the device will prompt the user and eventually cutoff, and after replacing the primary battery will be immediately ready to

use. The rechargeable battery can be incorporated into the device and not be available to the user.

Referring to FIG. 2, a circuit 30 to control the operation of the step- up (boost) DC/DC converter 12 to provide optimal requirements is shown. The circuit 30 includes bias and control circuits 32 for the DC-DC converter 12, a primary current sense amplifier and a power shutdown 34 and a charge cutoff switch 36. In addition, fuse protection 38 is supplied.

The step- up (boost) DC/DC converter 12 can be for example, an LTC 3400 (U_1) from Linear Technology. Many other devices could be used for example, the MAX 1765 from Maxim. The LTC 3400 (U_1) has excellent efficiency (>90%) at low current levels, compared to about 80% or less for most other parts. The biasing circuit 32 for the converter 12 includes an inductor L_1 (e.g., 6.8 uh) coupled across the converter 12, which is optimized to improve conversion efficiency. The input voltage range of the step-up (boost) DC/DC converter 12 in this example is from 0.7 to 5.5V. The output voltage is adjustable via two external resistors, R_1 and R_2. The output voltage is adjusted on the feedback input (FB) of the converter 12 to equal an internal voltage reference (e.g., 1.25V), when the output voltage is 4V on output (Vout). The output voltage should remain higher than the input voltage for the converter 12 to operate normally. The limit on output voltage level to 4.0 volts thus limits the input voltage range in this particular implementation to 0.7- 3.3V, which is applicable for one or two primary cells in series (alkaline, Zn-air), or one Li primary cell. Should the input voltage exceed the output with more than 0.7V, the body diode within the DC/DC converter chip will be forward biased and current will be transferred from the primary side to the secondary, limited only by the internal resistance of both batteries and the voltage difference between the two systems, resulting in a high inrush current.

The internal output current limit for this converter is 600 mA. A lower current limit, in the range 10-100 mA, is desirable to further improve efficiency and reduce size and cost. Ideally, the circuit 10 could be an ASIC, incorporating most of the external components (probably except the inductor L1 and the current sensing resistor, which can be used to program externally the primary current for the specific application). The capacitors C_1, C_2 and C_3 are used to filter switching pulses at the input and output of the converter 12 and prevent oscillations. C4 is used for "soft start" of the converter and to improve stability.

The circuit 30 has primary current sensor/amplifier with power shutdown section 34 including an operational amplifier U2 having resistors R_4 and R_5 to provide a primary current

sensing resistor. The value of resistors R_4 and R_5 is a very low value to provide a minimum voltage drop or (IR losses) across the resistor R_5 (e.g., 0.25 ohm at 100 mA). The very low (25 mV average) IR drop is amplified 50 times by the operational amplifier U_2, whose gain is set by the R_2/R_3 ratio to reach 1.25V at the output of a diode D_1, connected to the converter 12 feedback input FB. In this way, the output voltage signal across R1, and the input current signal, coming through the diode D1, are summed at the converter's feedback input, without interference in-between, on a "largest- only" basis, and compared to the internal reference voltage. The system reacts to whichever of the signals first reaches 1.25V, and stops the converter switching, thus reducing the output voltage. This provides a simultaneous constant output voltage/constant input current type of battery charging source.

The output voltage is limited to 4V, and the output current is also limited to: $I_{out} = I_{in} \times V_{in}/V_{out}$, which turns this voltage converter into a Li- ion charger, where CV/CC (constant voltage/constant current) output is required. Usually the Li- ion chemistry requires V= 4.1V or 4.2V, and I< 1C rate. In circuit 10, V= 4V and I<< 1C rate, which is much safer and may not require an additional protection board. If abnormal conditions are anticipated, redundant protections should be used (for example, applying higher voltage at the primary battery terminals may be unsafe for the system described earlier).

As the operational amplifier U_2 drains a few tens of microamps, when powered, a power-save shutdown mechanism is implemented in order to reduce the quiescent current of the system, using the shutdown pin of the operational amplifier U_2. When the converter 12 is active and switching, the pulses through the diode D_2 will decrease the voltage on the shutdown pin of the operational amplifier U_2 sufficiently to enable the operational amplifier U2, and when idle, current through the pull-up resistor R_8 will charge the capacitor C5 and cut-off power to the operational amplifier U2.

The circuit 30 also includes a switch circuit 36. The Li- ion cell is connected to the output of the DC/DC converter 12 through the MOS FET (metal oxide semiconductor field effect transistor) switch Q_1. The switch circuit 36 prevents discharge (several milliamps) of the Li- ion cell through the output of the DC/DC converter 12, when the primary battery during discharge reaches the cutoff voltage on the DC/DC converter 12 input side. The switch circuit 36 could also be used to tune the system primary cutoff voltage to a desired level for one or two cells in series of the selected rechargeable battery chemistry. The charge switch circuit 36 cuts off before

the converter 12 input cutoff voltage is reached. The example shown is for "one cell" alkaline implementation. MOSFET Q1 is biased through the emitter-collector junction of the bipolar transistor Q_2, and the base-emitter junction of the last is biased through R_7 from the primary battery. When the primary voltage drops under about 0.7V, Q_2 is off and turns off Q_1, stopping the charge. The resistor R_6 sinks the leakage current through Q_2 when open to prevent it from biasing the high-impedance gate of Q_2. As turning the charge "off" removes the load from the converter output Vout and hence from the primary battery, the voltage of the last increases and charging resumes, then the circuit 36 is activated again, thus switching until all available energy of the primary battery for the chosen cutoff voltage is transferred to the rechargeable battery 16. This approach distinguishes from other approaches, as normally a device will cut off when the cutoff voltage of its power source is reached for the first time, and some amount of energy will remain unused in the primary battery. The current approach allows the primary battery to deliver all of its energy prior to termination.

The Li- ion battery has a fuse circuit 38 with fuse (F_1) in series with both the charge path and the output, used for safety, to permanently open in case of a short- circuit condition.

There are several parameters to optimize when designing a hybrid power system. For example, the energy of the primary battery 14 is optimized to cover the desired total runtime of the device. The energy of the rechargeable battery 16 is optimized to cover the desired continuous runtime of the device for 1 cycle. The power of the rechargeable cell is selected to be adequate for the device peak power and the charge rate is optimized to allow nearly full primary battery use to satisfy a desired intermittent performance of the device.

This optimization is a compromise between efficiency, charge time, size and price from one side and performance from the other. In order to accelerate the charge, when the rechargeable battery is close to discharged state, a voltage- related charge rate could be implemented in the converter design, as with the MAX 1765 EV board from Maxim. As the Li+ charge voltage rises quickly in the 3V-3.7V region, the high rate charge lasts for a short time only and does not significantly affect the primary battery.

In the unlikely event of emergency use of the device just after the maximum continuous runtime has been used, the full power from the primary battery 14 may be provided to the rechargeable battery 16, at the expense of efficiency.

In many devices 20, a smaller than originally specified size Li- ion battery can provide the necessary peak power, and due to the permanent charging, may be sufficient for satisfactory continuous performance.

Referring to FIG. 3, an alternative circuit to control the operation of the step- up (boost) DC/DC converter 12 is shown. The circuit includes bias and control circuits for the DC-DC converter 12, a primary current sense comparator 64 and a charge cutoff comparator 66, connected to a power shutdown circuit 62. In addition, fuse protection 68 is supplied.

The step- up (boost) DC/DC converter 12 can be for example, the LTC 3400 (U_1) from Linear Technology. Many other devices could be used, for example, the MAX 1765 from Maxim, as mentioned above. The external components for the converter 12 include an inductor L_{11} (e.g., 6.8 *u*h) coupled across the converter 12, which is selected for optimal conversion efficiency. The input voltage range of the step-up (boost) DC/DC converter 12 in this example is from 0.7 to 5.5V. The output voltage is adjustable via two external resistors, R_{11} and R_{12}. The output voltage is adjusted on the feedback input (FB) of the converter 12 to equal an internal voltage reference (e.g., 1.25V), when the output voltage is 4.0V on output (Vout). The output voltage should remain higher than the input voltage for the converter 12 to operate normally. The limit on output voltage level to 4.0 volts thus limits the input voltage range in this particular implementation to 0.7- 3.3V, which is applicable for one or two primary cells in series (alkaline, Zn- air), or one Li primary cell. Should the input voltage exceed the output, current will be transferred from the primary side to the secondary, limited only by the internal resistance of both batteries and the voltage difference between the two systems, resulting in a high inrush current.

As above, a lower internal output current limit of the DC/DC converter, in the range 10-100 mA, is desirable to further improve efficiency, and reduce size and cost. This could be provided by an ASIC, incorporating most external components (probably except the inductor L1 and the current sensing resistor, which can be used to program the primary current value for the specific application). The capacitors C_{11}, C_{12} and C_{13} are used to filter the switching pulses at the input and output of the converter, and prevent oscillation. The capacitor C_{18} is used to assure "soft start" of the DC/DC converter.

The circuit 64 includes a primary current sensor/comparator, and power shutdown section 62, including an operational amplifier U5-A (one operational amplifier of a dual packaged op amp pair), having resistors R_{14} and R_{15} to provide a primary current sensing resistor, which

should have a very low value for minimum voltage drop (or IR losses) across the resistor R_{15} (e.g., 0.25 ohm at 100 mA). The very low (25 mV average) IR drop is compared to a reference voltage (produced by the reference voltage source D2 and the voltage divider R_{19}/R_{13}) by the operational amplifier U_2, whose output will go high and cut off the converter, when the primary current exceeds the preset limit. The resistor R_{20} and the capacitor C_{16}, connected in the negative feedback loop of the operational amplifier U5-A, form an integrator to introduce a delay and thus stabilize the comparator's response. The diode D1 prevents interference between the voltage control and the current control circuits. In this way, the output voltage signal, coming through R_{11}, and the input current signal, coming through the diode D1, are summed at the converter's feedback input, without interference in-between, on a "largest-only" basis, and compared to the internal reference voltage. The system reacts to whichever of the signals first reaches 1.25V, and stops the converter 12 switching, thus reducing the output voltage.

The Li-ion cell is connected to the output of the DC/DC converter through the MOS FET (metal oxide semiconductor field effect transistor) switch Q_{11}. The shutdown control circuit 66 prevents discharge (several milliamps) of the Li-ion cell through the output of the DC/DC converter 12, when the primary battery during discharge reaches the cutoff voltage on the DC/DC converter input side (in this example 1.4V for two alkaline cells in series). It could also be used to tune the system primary cutoff voltage to a desired level for one or two cells in series of the selected battery chemistry. The shutdown circuit 66 via Q_{11} cuts off before the converter input cutoff voltage is reached. MOSFET Q_{11} is biased through the output of an Op Amp U5-B that is used as a comparator to sense, via resistor R_{24}, when the input voltage to the DC-DC converter 12 is below a certain threshold. The threshold voltage is determined by resistors R_{17}, R_{23}, and Zener diode D2. In this example, a hysteresis is introduced by the use of R_{18} in the U5-B negative feedback loop. If V is 1.40 volts or less, the converter is shut down through the inverter circuit 62, formed by the transistor Q_{12}, and the charge is cut off via Q_{11}, preventing discharge of the Li-ion cell through the converter output. If V is 1.45 volts or more, the DC/DC converter is "on" and the circuit is charging. A signal "Replace Primary" is asserted when the input voltage is below 1.4V and is used to drive Q_{11} and Q_{12}. When the primary voltage drops under about 1.4V, Q_2 is off and turns off U_1, stopping the charge. The resistor R_{16} sinks the leakage current at the high-impedance gate of Q_{11}, when open, to prevent biasing. Turning the charge "off" removes the load from the converter output V_{out} and hence from the primary

battery, and the voltage of the primary battery recovers, turning the charge "on" again. The switching and hence charge will continue at attenuated duty cycle until all available energy of the primary battery for the chosen cutoff voltage is transferred, as above.

The Li- ion battery has a fuse circuit 68 with fuse (F_1) in series with both the charge path and the output, used for safety, to permanently open in case of a short-circuit condition.

A number of embodiments of the invention have been described, other embodiments are within the scope of the following claims.